

**Water Balance Study: A Component of the Watershed
Management Plan for the Carneros Creek Watershed, Napa
County, California**

prepared for

**Stewardship Support and Watershed Assessment in the Napa River Watershed: A
CALFED project
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Napa County Resource Conservation District

by

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Executive Summary

This is one of a series of technical reports prepared under a grant from the CALFED watershed program. It is intended to provide technical support for a watershed management plan for the Carneros Creek watershed, responding to stakeholder interest in water quantity issues.

A Thornthwaite-type water balance model was developed for the watershed, using estimates of monthly precipitation and potential evapotranspiration (PET) to estimate actual evapotranspiration (AET) and runoff, based on the estimated soil storage capacity for the watershed.

Data used include long-term monthly average rainfall at Napa State Hospital (NSH) and estimated monthly average values of PET provided by the California Irrigation Management Information System (CIMIS). NSH rain data are amplified by 15%, so that the rainfall in an average year is consistent with mapped information for Napa County. PET values are multiplied by a landscape coefficient that is a weighted average of estimated values for wooded grasslands, rural residential land, and vineyards. AET is estimated on the basis of PET by use of the original Thornthwaite method.

The model distinguishes between quick runoff, which runs off immediately without infiltration, and slow runoff, which contributes to soil moisture recharge before it enters the runoff stream. Quick runoff is estimated in the model by the use of a parameter which defines the fraction of monthly precipitation which runs off immediately; it is defined only for the period from December through March. Slow runoff is estimated each month on the basis of a second parameter, which defines the fraction of available water (water beyond that required to satisfy soil moisture needs) which runs off. There is no separate accounting of groundwater storage; rather, recharge of groundwater is included in total runoff.

The model was calibrated using flow information at Old Sonoma Road Bridge collected from December 2001 through June 2002. The model showed a tendency to overpredict total runoff, which may reflect the inclusion of groundwater recharge in runoff. The sensitivity of the model to variations in landscape coefficient and soil moisture capacity was explored.

The basic water balance for an average year was calculated (Figure 5), displaying typical characteristics of California streams, with a rainy season peaking in January and a dry season at its driest in July and August. Modeled streamflow begins to rise in December; it roughly follows the rise and fall of rainfall from then until midsummer, when the stream slows to a trickle. The model shows essentially no streamflow from September through November. Actual ET follows potential ET quite closely from October through April but then is reduced from the potential, as the ground begins to dry out; when rainfall begins to pick up again in September, actual ET begins to recover immediately as well.

Of the 710 mm of rainfall in an average year, a total of 371 mm runoff is estimated by the model, for an overall runoff coefficient of 0.52.

The model was used to simulate the water balance in years that were significantly wetter or drier than average. Two recent water years were selected, 1996-97 and 1986-87, with a rainfall total approximately one standard deviation above and one standard deviation below the mean, respectively. In both these extreme years, the model gives a convincing quantitative picture of the shifting water balance resulting from this particular distribution of rainfall over the water year.

Runoff estimated by the model for an average year compares favorably with an estimate prepared by the State Division of Water Rights for Carneros Creek and with a recent application of the Thornthwaite method in the Tomales Bay Watershed. However, comparison of these modeled values with regional work would suggest that both models are overpredicting runoff. The explanation may lie in the fact that both the Tomales study and the present work follow the original Thornthwaite method in not distinguishing groundwater recharge from surface runoff.

The model can be greatly improved as more local rainfall data and more years of measured flow become available. These data will make possible much more exact calibration of the model, so that the following potential additions to the model may be considered:

- Groundwater recharge and extraction
- Timing of withdrawals from the stream and their return to the atmosphere as ET
- Variation of vegetative cover, soil moisture capacity and precipitation through the watershed

These additions will require the development of data representing the variability of the relevant processes over the watershed and over the water year.

1. Introduction

This report describes the development of a water balance model for the Carneros Creek watershed in southwestern Napa County. It is one of a series of technical reports prepared under a grant from the CALFED watershed program, which will develop a watershed management plan for the Carneros Creek watershed on the basis of needs expressed by the Carneros Creek Stewardship, an active local group of environmentally concerned landowners and other residents. The stewardship group is concerned about the availability of water, both for human use and for fish habitat. The watershed is entirely rural, and the stewardship group includes farmers, ranchers, and rural residents.

Existing information on the water resources of this creek is sparse. Until December 2001, the stream was not gaged, although a recent staff report by the California State Department of Water Resources indicates that over 30 percent of the average unimpaired creek flow is allocated to water permit holders (Fortner, 2001). Some rural well owners have observed a decline in water levels in recent years. In 2001, a number of local water permit holders pooled their resources and paid for installation of an automatic recording streamgage on the creek, in order to be able to comply more readily with the terms of their various withdrawal permits. The new gaging station on the creek was established by Napa County Resource Conservation District.

These landowners and other Carneros watershed residents have asked for a water budget, to clarify their understanding of how much water is actually available for various uses in their watershed. The water balance model described below, which uses estimates of monthly precipitation and potential evapotranspiration to estimate actual evapotranspiration and runoff based on the estimated soil storage capacity for the watershed, is intended to be the first step toward such a budget.

The model does not include groundwater flow; rainfall which infiltrates beyond the root zone and recharges the groundwater is not distinguished from surface runoff. The model is calibrated using available streamflow measurements and can be used to predict water availability for different climate scenarios, such as a typical wet or dry year.

2. Study Area

Carneros Creek drains an area of approximately 23 km² (9 mi²) in southwestern Napa County. It is tributary to the Napa River, and like the Napa River it provides habitat to steelhead (*oncorhynchus mykiss irideus*), a federally listed threatened species, and other valuable native fish species. The greater part of the watershed is mixed oak woodlands and grasslands, dominated by annual grasses, which until fairly recently were heavily grazed. Approximately 20% of the watershed is planted in vineyards, and there are noteworthy patches of rural residential development, particularly in the lower reach of the creek downstream of Old Sonoma Road. There are a number of farm ponds in the watershed. Typical soils in the watershed are shallow clay loams. Like the rest of the

larger Carneros region, the Carneros Creek watershed has relatively low rainfall in the lowlands, although the higher elevations are distinctly wetter. The watershed is relatively long and narrow, and isopleth maps show average rainfall amounts increasing steadily as one moves up the valley. Elevations in the watershed range from sea level to 500 m (1640 ft). Snowfall is not significant.

The watershed is depicted in Figure 1.

3. Methods

There are a variety of simple water balance models available to describe runoff (or available water) on the basis of precipitation, and these models have been used with success to help quantify water availability based on monthly precipitation input and estimates of evapotranspiration losses. The water balance model developed here relies on a simple conceptual model developed originally by Thornthwaite, elaborated subsequently on various occasions, and restated in approximately original form by Dunne and Leopold (1978). In a recent study of the Tomales Bay watershed in neighboring Marin County, using the Thornthwaite model for multi-cell analysis of a 561 km² watershed, Fischer et al. (1996) noted their deliberate choice of the “original Thornthwaite model, rather than one of the various derivative models, because the original version of this model provides straightforward and explicit insight into water evaporative loss, internal storage, and runoff.” The simplicity of the model is appropriate to the present case, where data are limited and the need is for a clear conceptual model that will help identify data gaps and focus future data gathering efforts. The present work generally follows Dunne and Leopold.

The model has a number of sources of uncertainty as the price of its simplicity. Groundwater storage, as distinct from soil moisture storage, is not included, and any precipitation that enters groundwater storage is considered to leave the system as runoff. Similarly, any water taken from groundwater storage for surface use is not included, even though it may help meet the evapotranspiration need. The entire Carneros Creek watershed is treated as a single unit, with three principal independent variables: rainfall, potential evapotranspiration, and field soil moisture capacity. Each of the three variables is defined for the watershed as a whole, and any variation in space is not considered. Total monthly rainfall is based on available (daily) climate records, which although long-term are for a location outside the Carneros Creek watershed. Total monthly potential evapotranspiration is based on estimated average monthly values, and the model uses a monthly water balance approach to estimate actual evapotranspiration and runoff on a month-by-month basis. Calibration data are as yet limited. Nevertheless, in spite of these limitations the model should provide a good conceptual tool to understand the hydrology of the Carneros Creek watershed.

Potential evapotranspiration (PET) is estimated using monthly average ETo values published by CIMIS (California Irrigation Management Information System); ETo is a reference value of evapotranspiration defined for a standard crop taken to be 0.12 m (4.7

in.) high (CIMIS, 1999). This reference value is multiplied by an overall landscape coefficient that is a rough weighted average of estimated values for wooded grasslands, rural residential land, and vineyards; the greater this coefficient, the greater the water loss through evapotranspiration. Estimated values for each of these landscape types were derived using advice from CIMIS scientists (Anderson, 2002 and Temesgen, 2002) and a recent published guide (UC Cooperative Extension et al., 2000). The specific values and the overall landscape coefficient used in the water balance model are shown in Table 1. Application of this coefficient produces a value of *potential evapotranspiration* (expressed as an average rate for the entire area of the Carneros Creek watershed), for each month.

Table 1. Landscape Coefficients

<i>Landscape type</i>	<i>Specific Coefficients</i>		<i>Lumped Coefficient</i>	<i>Weighting Factor</i>
Woods and grass	Oak trees	1.2	0.55	0.6
	Annual grass, not irrigated	0.4		
Rural residential	Moderate vegetative water use	0.5	0.6	0.2
	Paving	0.0		
	Open water	1.25		
Vineyards	Low vegetative water use	0.25	0.25	0.2
<i>Overall Landscape Coefficient</i>			0.50	1.0

Actual ET corresponds to PET in the model as long as there is sufficient monthly rainfall, but as the soil dries the actual ET is less than PET. The reduction in actual ET is quantified using the original method from Thornthwaite and Mather's manual, presented in Dunne and Leopold (1978) as a graphical relationship between accumulated potential water loss and water retained in the soil. Field soil moisture capacity is estimated at 125mm, using Thornthwaite and Mather's suggested water capacity of 25% for clay loam soil but with a reduced rooting depth of 0.50 m, because much of the Carneros watershed has a shallow clay pan which limits rooting depth. This rooting depth represents a rough average for the variety of vegetation present in the watershed; the calculation is illustrated in Table 2. Below this average depth, infiltrated precipitation is considered to become groundwater recharge.

Table 2. Rooting Depths

<i>Landscape Type</i>	<i>Typical Rooting Depth, m</i>		<i>Average Depth for Landscape Type, m</i>	<i>Overall Weighting Factor</i>
Woods and grass	Oak trees	1.00	0.44	0.6
	Annual grass, not irrigated	0.30		
Rural residential	Moderate vegetative water use	0.50	0.38	0.2
	Paving	0.00		
	Open water	1.25		
Vineyards		0.80	0.80	0.2
<i>Overall Average Rooting Depth</i>			0.50	1.0

The water balance model is generally applied as a single-storage model. In cases where immediate storm runoff makes up a large fraction of total streamflow, however, the use of more than one storage component may be necessary. In order to determine whether Carneros Creek is one of these cases, a rough baseflow separation was carried out by graphical means, on the basis of a recent limited record of flow in Carneros Creek (described under data, below). The results indicated that approximately 40% of the streamflow during the measured period was direct stormflow. Since direct stormflow appears to be significant, the Thornthwaite model was altered to include two parallel storages, one quick and one slow.

The model has two calibration parameters, the quick runoff constant (RO_{quick}) and the slow runoff constant (RO_{slow}). RO_{quick} is defined as the fraction of a month's rainfall that immediately becomes streamflow, principally for one of two reasons: either the soil storage capacity is exceeded or the precipitation rate exceeds the soil infiltration capacity. This parameter may also help account for spatial variability in precipitation, PET and soil characteristics which cause locally elevated runoff.

After quick runoff, soil moisture demands and ET are satisfied, and the amount of surplus water available each month is determined, RO_{slow} is defined as the fraction of that surplus that runs off in a given month. RO_{quick} is set to zero in all months except December, January, February and March, on the basis of local observation and the limited flow record available.

4. Data

The rainfall data used in this model are long-term monthly averages from the California Data Exchange Center (CDEC, no date), for station NSH located at Napa State Hospital. The period of record is nearly 100 years long, from 1905 to the present. The average annual precipitation is 617 mm (24.3 in.). The station is located some 5 km (approximately 3 mi) from the Carneros Creek watershed, but it is the closest station with

a long-term record. Rainfall data from this station are applied with an amplification factor of 1.15, for a total annual precipitation of 710 mm (28 in.), on the basis of the isohyetal map of Napa County displayed in Figure 2, where it is evident that an interpolated line at 28 in. average annual precipitation would approximately bisect the essentially linear watershed.

Values of reference transpiration ETo were obtained from the CIMIS web site, also in the form of monthly average values. They are specific to climate zone 5, a relatively small zone confined to portions of three North Bay counties. Owing to the scale of the CIMIS climate zone map, there is some uncertainty about the appropriate zone for the Carneros Creek watershed, but climate zone 5 seems to be most representative. The monthly values total 1115 mm (43.9 in.), nearly twice the total annual average rainfall at station NSH.

Although there are no long-term flow records for this creek, a continuous discharge record is available from a newly-established gaging station at Old Sonoma Road Bridge, beginning on December 12, 2001. The record from that date through June 2002 was used for the baseflow separation mentioned above and for limited calibration work. Although the station is new, a satisfactory rating curve has been developed on the basis of six separate discharge measurements ranging from 0.07 to 6.79 m³/s (2.4 to 239.8 ft³/s) during the period of record. This stage-discharge rating curve was used together with a continuous record of water level at the site to produce the continuous discharge record for the site. The record is judged by Napa County Resource Conservation District, the responsible agency, to be of good quality. The discharge record is shown in Figure 3, along with the baseflow separation. The baseflow separation was done by eye, joining by a straight line the point where the curve starts to rise and the point where it begins to flatten.

5. Model calibration

The calibration parameters were initially set using the best available information. RO_{slow} was set at 0.5, following Thornthwaite's guidance (Dunne and Leopold, 1978). RO_{quick} was set as follows: on the basis of extensive local experience, quick runoff was limited to the four months from December to March. Annual hydrographs from Dry Creek, a nearby Napa River tributary, typically do not show obvious direct stormflow outside this period, and the brief flow record for Carneros Creek follows the same pattern. The baseflow separation carried out using the flow record from 2001-02 showed 45% of the measured flow from December 12 through March as direct storm runoff. However, in this particular winter much rain fell before December 12, and direct storm runoff had begun in earnest; it is reasonable to assume that in a typical year, and including all of December, there would be distinctly less direct storm runoff. Following this reasoning, RO_{quick} was set at 0.4. There is considerable uncertainty associated with this value. However, overall runoff is not sensitive to it, because actual ET is almost always equal to PET during the winter, so the principal effect of changing RO_{quick} is to

vary the distribution of runoff between months of heavy winter rain and the following months.

To calibrate the model, it was run using amplified NSH rainfall for water year 2001-02 and the resulting streamflow compared to monthly totals from the gage record. The comparison is shown in Figure 4. It should be noted that the measured flow record presented in Figure 4 has been converted into millimeters on the basin, with water volumes divided by the drainage area at the gage site. This comparison needs to be used with caution, for several reasons. First, the rainfall record is derived from a single gage, one located several miles away from the watershed, and may not have been representative of the Carneros Creek watershed during this period. Second, the modeled streamflow does not take into account the timing of human withdrawals of water from the stream. Finally, the model does not distinguish recharge of groundwater storage from runoff. Due to these limitations, a fine-tuning of the calibration parameters was not warranted.

The measured streamflow for December is for less than a full month, so it is appropriate that the modeled flow is higher. In the remainder of the period of comparison, it is noteworthy that the modeled flow is high through the winter but slightly low after that, a variance that cannot easily be changed by altering the calibration parameters. The overprediction of runoff which is strongly evident overall may be due to the inclusion of groundwater recharge in runoff; a more complicated model which takes separate account of groundwater storage might be able to reduce overall runoff and allow some return flow to the stream through the spring months

The sensitivity of the model to variations in the landscape coefficient and the soil moisture capacity was explored. As one would expect, changes in either of these parameters affected total runoff significantly. Increasing the landscape coefficient, which increases the potential ET, has the effect of reducing total runoff. Increasing the soil moisture capacity, which means that more water is held in the soil and is available to satisfy potential ET, has a similar effect. Table 3 shows the change in total runoff for varying values of the landscape coefficient and the soil moisture capacity.

It is interesting to note that varying *ROslow* had very little effect on total runoff.

Table 3. Variation of Total Runoff with Landscape coefficient and Soil moisture capacity

<i>Parameter</i>	<i>Value</i>	<i>Percent Change in Total Runoff</i>
Landscape coefficient	0.45	+ 3.5
	0.50	-
	0.55	- 3.7
Soil moisture capacity	100 mm	+ 5.4
	125 mm	-
	150 mm	- 4.8

6. Model Application

The basic water balance for a hypothetical average year is shown in Figure 5. The average year is based on average monthly rainfall amounts, and may not necessarily be representative of measured rainfall for a given year. The figure shows some of the typical characteristics of California streams, with a rainy season peaking in January and a dry season at its driest in July and August. Modeled streamflow does not begin to rise until December, which agrees with common experience in Carneros and other local watersheds; it roughly follows the rise and fall of rainfall from then until midsummer, when the stream slows to a trickle. The model shows essentially no streamflow from September through November. Actual ET follows potential ET quite closely from October through April but then is reduced from the potential, as the ground begins to dry out; when rainfall begins to pick up again in September, actual ET begins to recover immediately as well.

Of the 710 mm of rainfall in an average year, a total of 371 mm runoff is estimated by the model, for an overall runoff coefficient of 0.52.

The model was used to simulate the water balance in years that were significantly wetter or dryer than average. Two recent years were selected, with a rainfall total approximately one standard deviation above and one standard deviation below the mean, respectively. For each, the same average monthly CIMIS PET values were used as for the average year. The results are shown in Figures 6 and 7.

In the wet water year 1996-97, there was very high precipitation in December and January and after that generally below average rainfall, with a couple of spikes in the dry season. Total precipitation for the water year is 943 mm (37.1 in.). The direct storm runoff is highest in December and January, so that total streamflow is dramatically increased, but the streamflow curve declines appropriately when rainfall drops off. Actual ET as modeled is believable, including a spike in August in response to a burst of unseasonable rain.

In comparison to the average year shown in Figure 5, the wet year has proportionally higher runoff. Out of the total precipitation of 943 mm, 647 mm (25.5 in.) runs off, for a total runoff coefficient of 0.69. This is explained by the particular timing of rainfall in the wet year. The extra rainfall comes in December and January and does not lead to any increase in ET; and since the rainfall is actually below average from February through April, the ground dries out early and actual ET is below that of the average year from March through July.

In the case of the dry water year 1986-87, shown in Figure 7, there is slightly higher than average rainfall during February and March, but otherwise rainfall is low, for an annual total of 456 mm (17.9 in.). The streamflow curve builds slowly to March and then drops off quickly, because there is very little surplus subject to slow runoff. Actual ET is lower

than in an average year, because the ground dries out quickly in April and stays that way. The overall runoff coefficient is 0.52, virtually the same as that for the average year because actual ET is so low. In both these extreme years, the model gives a convincing quantitative picture of the shifting water balance resulting from this particular distribution of rainfall over the water year.

For purposes of comparison, the modeled values of total runoff in acre feet per annum appear together with a runoff estimate used by the State Division of Water Rights in their processing of water rights applications (Fortner, 2001) in Table 4. The DWR value is estimated on the basis of a measured flow record on a nearby stream, Dry Creek. As in the earlier calculations, these values do not take into account any withdrawals by water users beyond the modeled evapotranspiration.

Table 4. Total runoff, various years

<i>Year</i>	<i>Total runoff, ac-ft per annum</i>
Dry Year, 1986-87	4,453
Wet Year, 1996-97	12,220
Average year	7,017
Average year, DWR value	6,381

The average-year runoff coefficient of 0.52 compares favorably with a recent application of the Thornthwaite method in the nearby Tomales watershed, where an average runoff coefficient of 0.56 was obtained (Fischer et al, 1996). However, comparison of these modeled values with regional work done by S. E. Rantz would suggest that both models are overpredicting runoff (Rantz, 1974). The explanation may lie in the fact that both the Tomales study and the present work follow the original Thornthwaite method in not distinguishing groundwater recharge from surface runoff.

7. Conclusion

The water balance model developed using the Thornthwaite method has given a preliminary qualitative analysis of the changing balance of rainfall, evapotranspiration and streamflow in the Carneros Creek watershed over the water year, accounting separately for quick and slow runoff responses.

The model can be greatly improved if more local rainfall data and more years of measured flow become available. The Napa County Resource Conservation District intends to maintain the gaging station on Carneros Creek, if ongoing funding can be found. There is a private network of local weather stations at various farm locations in Napa County, and rainfall has been measured in the Carneros Creek watershed for several years. The Carneros Creek stewardship group may be able to make these data available. In addition, available historical precipitation records from surrounding locations, such as Sonoma, can be included in the analysis to help develop a distributed estimate of precipitation over the watershed. If these rainfall and flow data can be obtained, the

model will be based on more representative rainfall and the calibration opportunities will be vastly improved.

With the opportunity of improved calibration, it may be possible to account separately for groundwater recharge and extraction in the model. Extending the model in this way will have the added benefit of clarifying the apparent contradiction between the modeled runoff and earlier regional studies. Although the modeling of groundwater was beyond the scope of the present study, the Carneros Creek Stewardship has begun a well monitoring program, which may provide useful data for such a model extension.

The effect of water withdrawals from the stream has already been included in the model in the landscape coefficient, insofar as the withdrawn water is used to water plants; the landscape coefficient reflects the water use of the vegetation in the watershed. However, the specific timing of the withdrawal of the water, its return to the soil by irrigation, and its exit from the system as ET have not been considered. It may be possible to vary the calibration parameters *ROquick* and *ROslow* over the water year, so that both the *increased storage* as farm ponds are filled (typically in December and January) and the *delayed release* over the growing season are appropriately handled. This will require information from water users and adequate calibration data. Model improvements of this sort will be relatively easy to carry out, given the necessary new data and information on water use practices.

One may also consider the use of a multi-cell model, which will make it possible to vary the landscape coefficient, soil moisture capacity and precipitation throughout the watershed. Improving the model in this way can be relatively time-consuming, but it is worth considering a limited multi-cell model. A simple subdivision of the watershed into a handful of sections on the basis of differing precipitation and land use may be relatively easy to carry out.

7. References

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8. Acknowledgments

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Figure 1. Carneros Creek Watershed

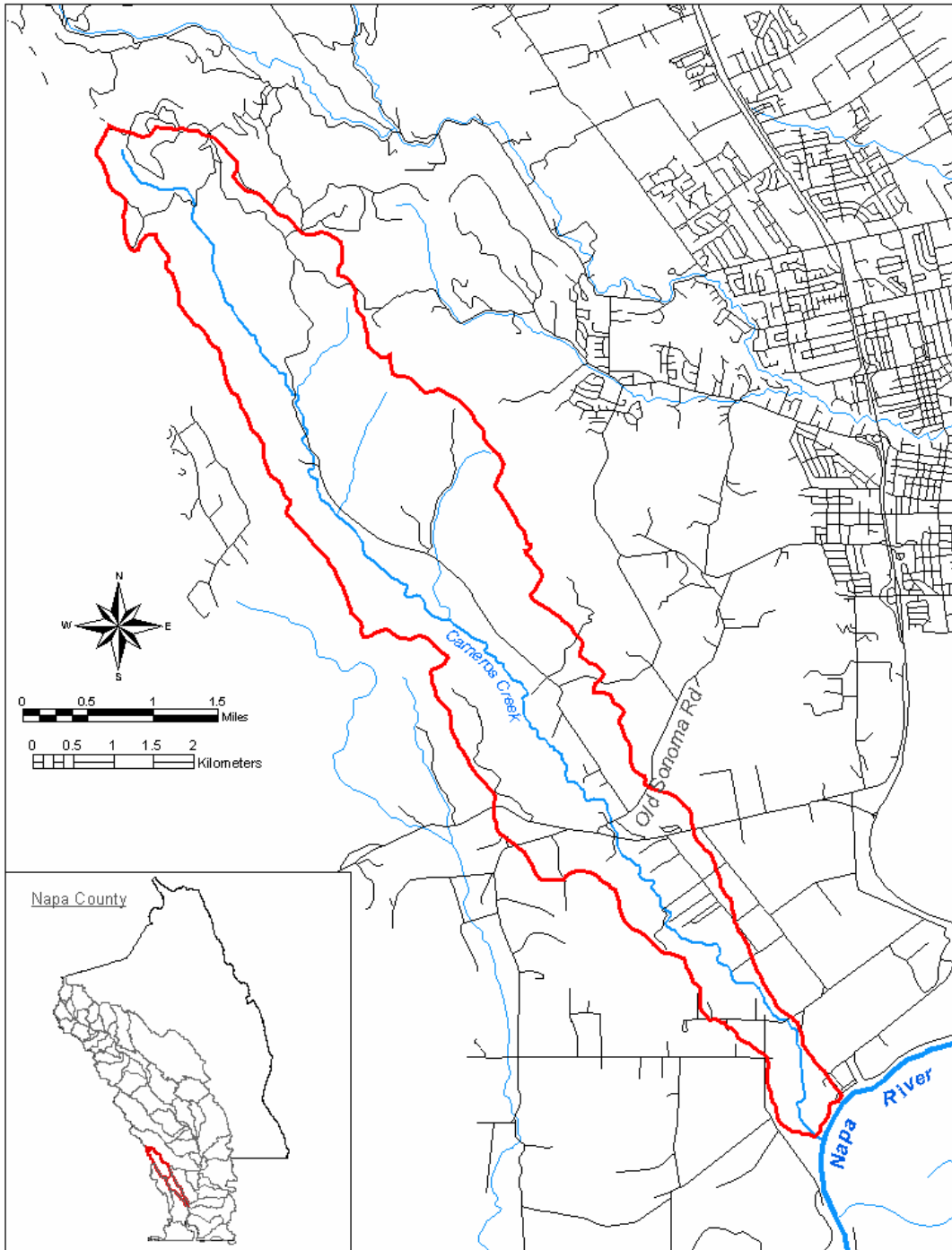
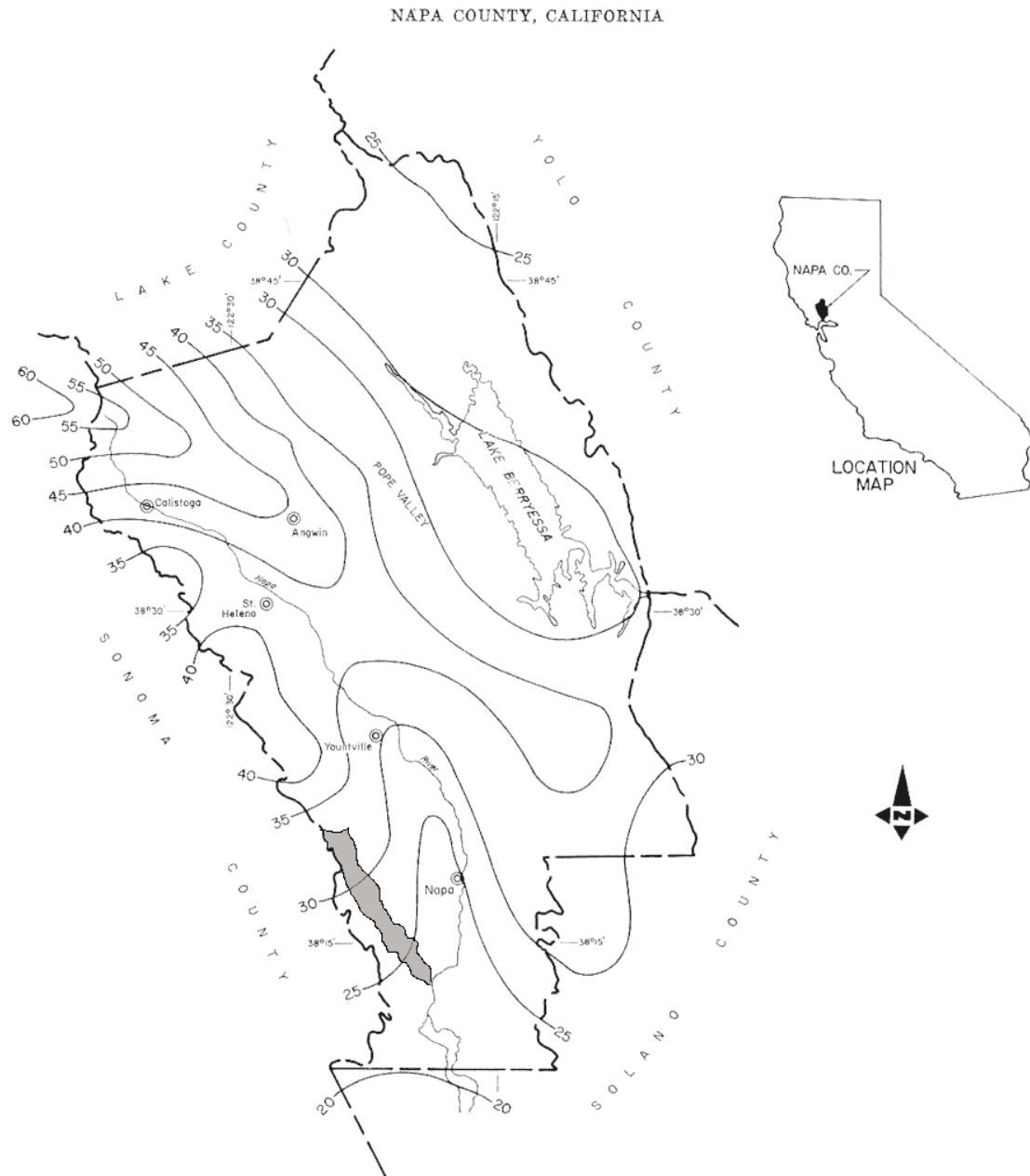


Figure 2. Average Annual Precipitation in Napa County, showing Carneros Creek Watershed (in gray)



source: G. Lambert and J. Kashiwagi, *Soil Survey of Napa County, California*, USDA-SCS, 1978

Figure 3. Discharge Record, 2001-02, with Baseflow Separation

Q, Carneros Creek at Old Sonoma Road

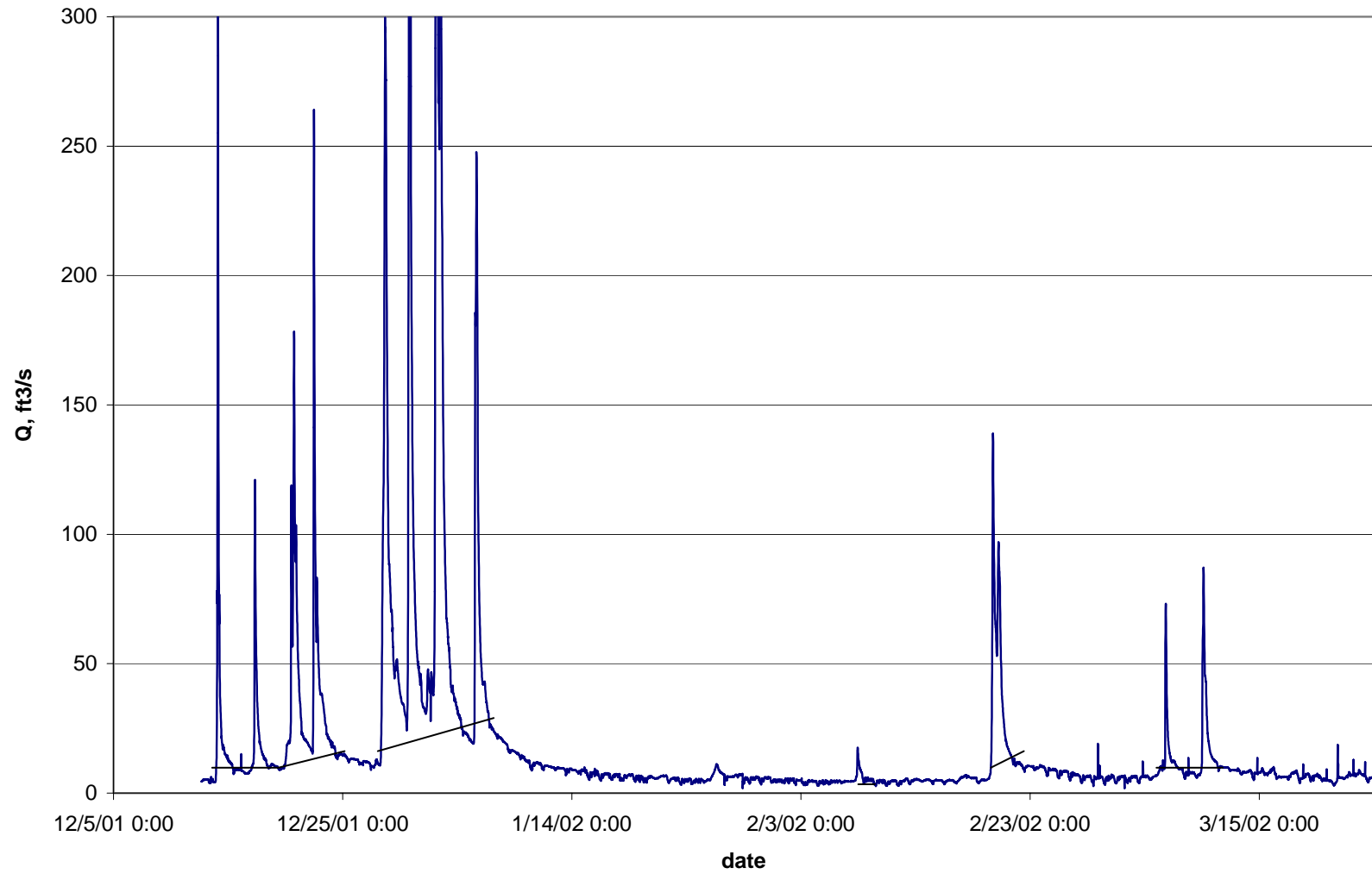


Figure 4. Carneros Mean Monthly Streamflow, 2001-02

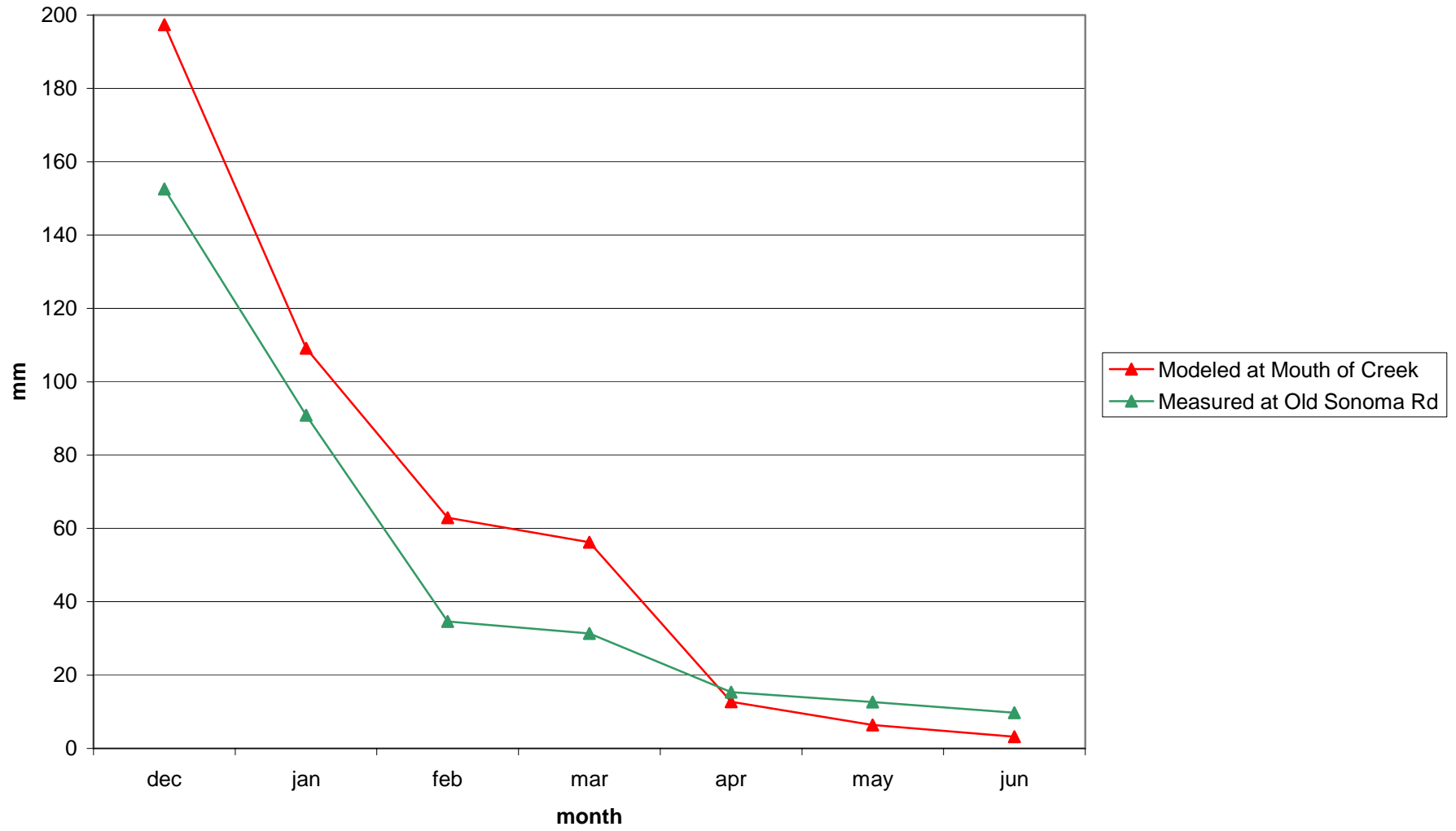
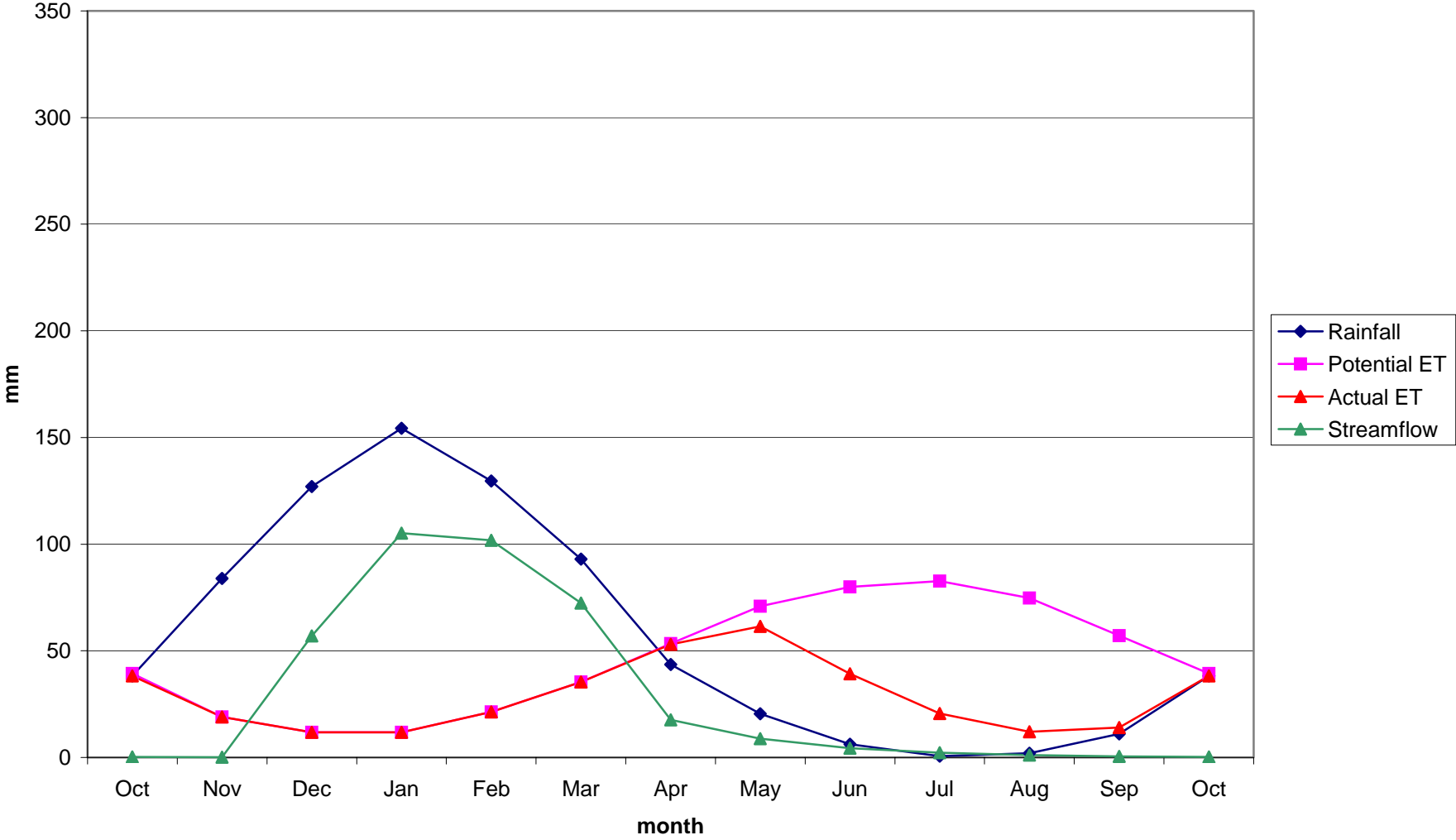
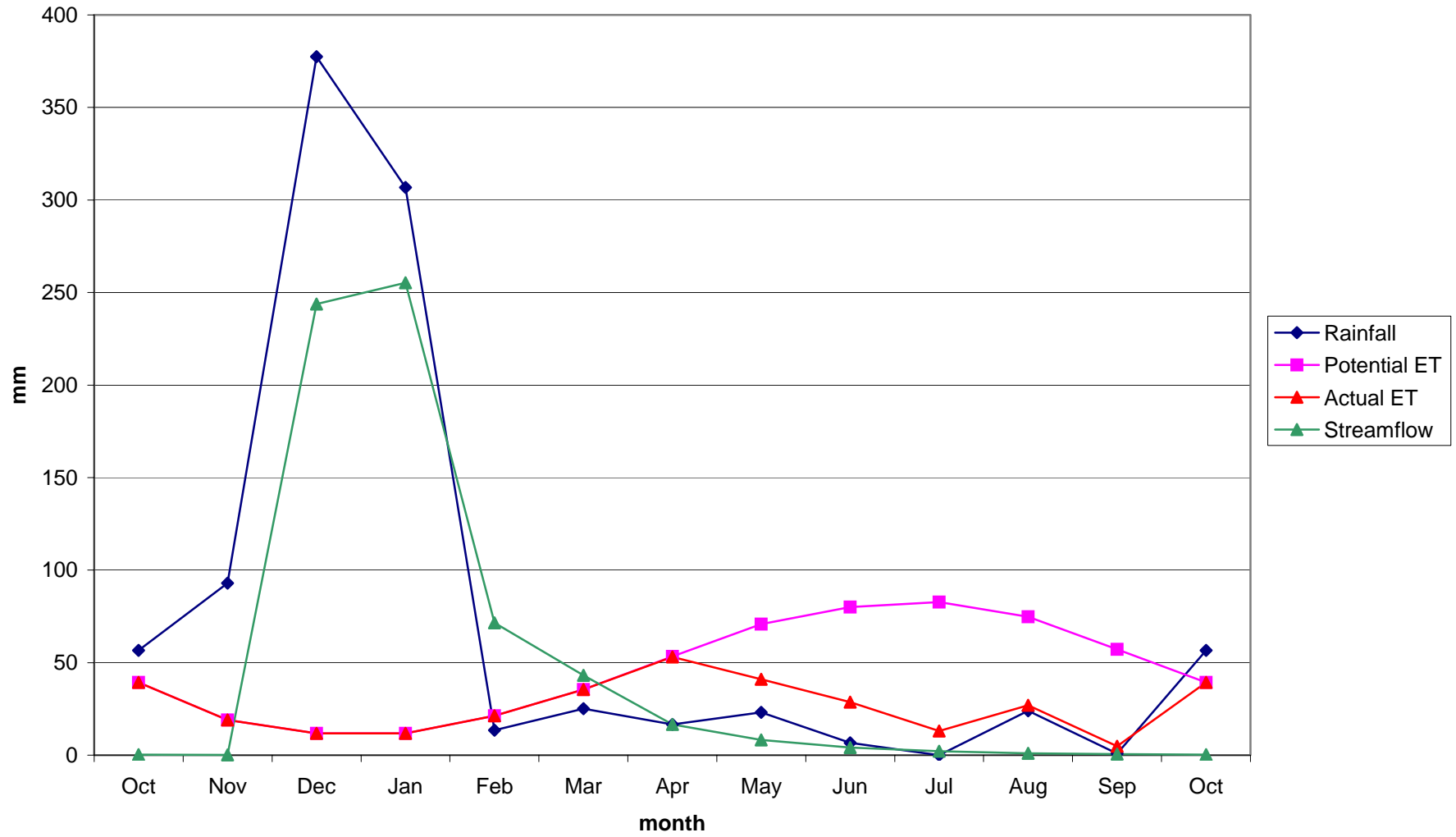


Figure 5. Water Balance for Carneros Creek
Average Year



**Figure 6. Water Balance for Carneros Creek
wet year**



**Figure 7. Water Balance for Carneros Creek
dry year**

